Experimental assessment of thermoelectric cooling on the efficiency of PV module.

Seepana Praveenkumar[1‡], Ephraim Bonah Agyekum [1], Naseer T. Alwan[1, 2], Mohammed A. Qasim [1], Vladimir Ivanovich Velkin [1], and Sergey E. Shcheklein [1]

[1] Department of Nuclear and Renewable Energy, Ural Federal University Named after the First President of Russia Boris, 19 Mira Street, Yekaterinburg, 620002 Yeltsin, Russia.

[2] Kirkuk Technical College, Northern Technical University, 36001 Kirkuk, Iraq

(Seepanapraveenkumar5@gmail.com, agyekumephraim@yahoo.com, nassir.towfeek79@gmail.com, mkasim@urfu.ru, v.i.velkin@urfu.ru, , s.e.shcheklein@urfu.ru)

[‡] Corresponding Author; Seepana Praveenkumar, Ural Federal University Named after the First President of Russia Boris, 19 Mira Street, Yekaterinburg, 620002 Yeltsin, Russia, Tel: +7 (963) 854- 35-66, seepanapraveenkumar5@gmail.com

Received: 17.05.2022 Accepted: 18.07.2022

Abstract- Solar photovoltaic (PV) energy is currently among the most utilized energies within the renewable energy (RE) industry for the generation of electricity. The technology which is used in converting the solar radiation into electrical power however has some demerits, one of which is its dependence on its operating temperature i.e., it's performance decreases with increase in temperature. This study therefore used a thermo-electric cooling mechanism to cool a PV panel under real weather conditions. Results from the experimental process shows a significant temperature reduction in the modified PV module (i.e., cooled panel), an average temperature of 33.37 °C was recorded for the cooled PV module against 45.60 °C. This is a 12.23 °C reduction in the PV module temperature which resulted in an electrical efficiency enhancement of 5.07%. The economics of the module suggests that the cooled module registered a levelized cost of electricity (LCE) of 0.410 $/kWh for a 365-day period whiles the referenced module recorded 0.414 $/kWh for the same period. An amount of 1.247$/kWh was recorded by the cooled panel for the 120-day period whiles the referenced module recorded 1.265 $/kWh. Despite the relatively high investment cost of the cooled module due to the extra cost associated with the cooling system, it still recorded a relatively lower LCE. This is due to the high power it generated during the experimental period.

Keywords: Photovoltaic module cooling; solar power plants; efficiency enhancement; thermodynamic analysis

1. Introduction

Issues such as economic growth, rise in population and technological advancement has led to an increase in energy consumption globally, this has led to increase in pollutions due to the emission of greenhouse gases (GHG) into the environment [1], [2]. Research has shown that CO_2 emissions alone contribute about 76% of the total of GHG emissions globally, with the power sector contributing around 41% of the world's CO_2 emissions [3], [4].

Renewable energy (RE) use is an alternative source of energy generation which is fast increasing around the world. One of the most widely used of such resources is solar energy especially in Africa and Asia where sunshine is abundant [5], [6]. The photovoltaic (PV) technology is a highly used technology within the solar energy industry [7]–[9]. A standard silicon-based solar cell has an electric conversion efficiency which ranges from 16 -20%. Under standard test conditions (i.e., 1000 W/m^2, and 25 °C), some newly manufactured silicon modules can transform up to 24.4% of solar irradiance to operational electricity [10]. Although solar PV technology is widely used globally, it comes with its challenges, the technology is significantly affected by environmental conditions which ultimately affect its output performance. The PV cell which is made up semi-conductor which converts the solar irradiation to electrical power has most of its energy absorbed from the sun lost through waste heat [11] [12]. Due to this shortcoming in relation to the PV technology it is imperative to improve the PV cells performance to make maximum use of it.

Several studies have reported on different mechanisms to stabilize a PV module' temperature to improve their productivity, this includes passive and active cooling mechanisms. Active cooling uses a coolant to cool the PV module, some of these coolants are water or air which usually need power for a fan or motor. In the case of passive cooling, the PV cell's temperature is reduced without consuming power [13]. Studies such as [14], [15] experimentally assessed different mechanisms of cooling a PV module. They evaluated the effect of cooling a PV with coir pith, greenhouse cooling, plant cooling, greenhouse + plant cooling, and phase change material (PCM) cooling on a PV module. Their results indicate that the coir pith cooling recorded the highest maximum percentage in the improvement of power which was 11.34%. A water spraying cooling technique was adopted by [16] for temperature management of a PV panel. The outcome of their experiment demonstrates that a maximum increase of 16.3% in the output power and an effective electrical efficiency improvement of 5.9% is possible.

Bahaidarah et al. [17] also analyzed the effect of incorporating at the back of a PV panel a heat exchanger for cooling purposes both experimentally and numerically. The outcome of the experimental measurements and the numerical analysis were found to be in a good agreement. The results suggest that the PV module's temperature could be reduced by some 20% which led to an efficiency improvement of 9%. A numerical study by [18] used single turn pulsating heat pipes (PHP) for temperature management of PV panel. They compared a copper fin with similar proportions as that of the PHP for cooling of PV panel. The outcome of their study identified the PHP as the best option for PV model cooling. It identified that the use of the PHP could help to enhance the electrical power by 18%. A mechanism that cools both surfaces of the PV module was proposed by [19]. The approach proposed by them resulted in a temperature reduction of 23.55 ℃ causing an improvement of 30.3% power output for the PV module. It also resulted in an electrical efficiency enhancement of 11.9%.

Furthermore, [20] suggested a porous cooling channel for the cooling of a PV module using a numerical model and an experiment. The outcome of the study proved that the non-uniform holes scattered close to the cooling water's outlet experienced a better cooling outcome. The PV panel integrated with the innovative cooling channel recorded an efficiency that is 4.17% higher than the uncooled module. A study by [21] also proposed a combination of PCM and aluminium fins to cool a PV panel under hot temperature situations. The method helped to reduce the temperature by 12.13 ℃ which occasioned an electrical efficiency enhancement of 5.15%. Salmin et al. [22] performed an experimental study using free and forced air for PV panel cooling along with aluminium fins. The results shows that the forced air convection led to a temperature drop of 11% whiles that of the natural air recorded 5.4%. Bokor et al. [23] constructed an adjustable setup for passive air circulation for the removal of accumulated heat in PV panels. Their study found out that the temperature 30-40 K can be reduced with the use of an adjustable passive air-cooling mechanism. Libbi et al. [24] combined a self-cleaning technique and an active mechanism to simultaneously cool a PV system. The hybrid technique used forced air circulation to actively cool the PV module's backside. The outcome of the experiment shows that their cooling mechanism was able to averagely decrease the panel's temperature by 15 ℃ which led to an electrical efficiency enhancement of 5.7%.

Salameh et al. [25] also proposed the use of a cold air form a Heating, Ventilating and Air Conditioning (HVAC) for the reduction of PV panel temperatures. The study revealed that an increase in the mass flow rate of the air from the exhaust has the potential to decrease the module's temperature. The efficiency of the module increased from 11% to 18% for a cooling load between 0-160 kW under solar radiation intensity of 500 W/m^2. Dida et al. [26] developed a passive cooling approach to mitigate increase in temperature for a PV module. The proposed system used water evaporation and capillary action of a burlap cloth for the cooling of the module. They concluded that the proposed system could lead to a temperature reduction of 20 ℃ which caused a 14.75% rise in the module's electrical efficiency. Kane et al. [27] employed active heat cooling using thermoelectric module (TEM) for temperature management of PV modules, this was done through a simulation analysis. Their mechanism was able to improve the PV module's electrical efficiency in the range of 1 – 18% for a temperature and solar irradiation rate of 25–45 °C and 0.8– 1 kW/m^2. Another study by [28] employed the passive cooling mechanism to cool a PV panel. They proposed the installation of PV panels on the surface of canals or rivers in order be cooled by natural evaporation. Their cooling approach led to a temperature reduction of about 7 - 16 ℃ which caused an electrical efficiency enhancement of about 12.12% - 22.9%. Ejaz et al. [29] also proposed the use of PCM and metallic foam-based system for temperature regulation of a PV panel. The outcome of their study shows that the configuration with a 12 mm foam thickness and PCM obtained the highest efficiency. Lucas et al. [30] assessed the possibility of using evaporative cooling to manage a PV module's temperture. They employed the photovoltaic evaporative chimney as the cooling mechanism. The obtained results shows that their proposed mechanism was able to improve the electrical efficiency by some 4.9% averagely. An active cooling approach was adopted by [31] to cool a PV module through a numerical study. They used flowing water to actively cool the PV module. The highest efficiency enhancement of 17.12% was observed at a solar irradiance of 1000 $W\ m^{-2}$, temperture of 45 °C and water velocity of 0.9 m/s. An experimental and economic assessement of a passive cooling method using planar reflector and fins was investigated by [32]. Their study shows that the use of lapping fins can lead to a temperature reduction of 24.6 ◦C. In order studies [33] assessed the effect of a cooling method, based on forced ventilation and spray cooling. Their cooling approach was able to reduce the PV module's temperature by 26.4 ℃

on hot sunny days. The impact of the spraying system on the PV module led to an efficiency of 14.3% for the cooled module compared to 12.7% for the uncooled module. Kabeel et al. [34] also employed three different scenarios, i.e., forced air cooling technology, water cooling technology, and forced air and water technologies, all integrated with reflectors for the cooling of PV modules. The study revealed that the use of reflectors and water cooling technology is the best option for PV module cooling. Amber et al. [35] experimentally assessed the impact of two different passive cooling methods (i.e., rectangular and circular fins) on a PV module's performance. Results from their study revealed that the rectangular fins reduced about 155% more heat and produced 4% and 10.8% more power than the circular fins and reference module's, respectively.

Finally, Nasrin et al. [36] analysed the impact of Water/MWCNT nanofluid based cooling approach on the performance of a PVT system experimentally and numerically. The experimental results and the numerical response agreed positvely. The percentage of enhancement for the water cooled system was found to be 9.2%. A study conducted by [37] showed that using a heat sink with flared-fins can minimize the thermal resistance by about 10%. Also, Baloch et al. [38] performed both numerical and experimental analysis on a converging channel heat exchanger for the cooling of PV. By using their proposed method, the temperature of the cell was reduced from 71.2 °C to 45.1 °C in the month of June.

It is therefore possible to state that temperature of a PV cell has proven to be key in the PV module's performance relative to energy generation. It is for this reason that the studies reviewed above proposed different mechanisms to reduce the PV modules operating temperature. It is however important to state that most of these mechanisms are bulky to construct and quite expensive, hence new ways of cooling the PV module devoid of these negatives ought to be proposed. It is for that reason that the current study assesses the use of thermoelectric cooling "Peltier Cooler" technique to cost effectively cool the PV module. This study is performed under real weather conditions unlike [27] who conducted a numerical study.

The organization of the paper is presented as follows: the materials and the method used for the experiment and analysis is presented in section 2. Section 3 covers the results and the discussion of the findings, whiles the conclusion is in section 4.

2. Materials and Methodology

This section describes the composition of things used in building of the test rig and the mathematical relations employed for the computation of the results. The experiment took into consideration two panels, one known as the cooled panel and the other reference module. The cooled module is

$$P_{mp} = V_{mp} \times I_{mp} = V_{oc} \times I_{sc} \times FF \tag{1}$$

integrated with the thermo-electric cooler whiles the referenced module has no modifications.

2.1. Mathematical Modelling

PV module's efficiency is largely dependent on its temperature and the ambient air temperature, since the current and voltage of the PV panel is subject to the temperature. Eq. (1) can be used to calculate the PV module's maximum power [21], [39].

Where V_{oc} signify the open circuit voltage, FF represent the fill factor, the short circuit current is denoted by I_{sc}, m signify the maximum power point on the I-V curve of the PV panel. Increasing the temperature of a PV module significantly affect the FF and V_{oc}, they reduce with an increase in the module temperature, this is due to the domination of the electrical properties of the semi-conductor by the thermally excited electrons, whiles the I_{sc} increases but only slightly [19], [39].

The efficiency of the panel is the ratio of the generated output energy to the input energy obtained from the sun, which is calculated using Eq. (2) [40].

The efficiency of the panel is the ratio of the generated output energy to the input energy obtained from the sun, which is calculated using Eq. (2) [40].

$$\eta = E_{out}/E_{in} \tag{2}$$

Eq. (3) is the mathematical relation which can be employed to estimate the efficiency of a PV module η_{pv} [19], [21], [41]

$$\eta_{pv} = \eta_{rT} \cdot \left[1 - \beta\left(T_{pv} - T_{rT}\right)\right] \tag{3}$$

In this case, the efficiency of the panel under reference temperature conditions i.e., 25 ℃ is denoted by η_{rT}, the temperature of the PV is also represented by T_{pv}, β symbolize the temperature coefficient of power in this study it is taken as 0.004 K^{-1}. T_{rT} denote the PV module's reference Temperature's effect on a PV module can be assessed using the mathematical relationship as presented in Eq. (4) [40], [42].

$$P_{pv} = Y_{pv} \cdot f_{pv}\left(G_T/G_{T,STC}\right)\left[1 + \alpha_p\left(T_C - T_{C,STC}\right)\right] \tag{4}$$

The derating factor for the PV module is denoted by f_{pv} (%), the rated PV array capacity is denoted by Y_{pv} (kW), the temperature coefficient of power is represented by α_p (%/°C), the incident solar radiation at STC is represented by $G_{T,STC}$ ($1 kW/m^2$), G_T (kW/m^2) signify the current time step solar radiation, the temperature of the PV cell at STC is denoted by

$T_{C,STC}$ (25 °C), and the current time step temperature of the PV module is denoted by T_C (°C).

Using a PVsyst software the effect of temperature on the efficiency and I-V characteristics of a 30 W PV module are simulated and presented in Fig. 1 and 2.

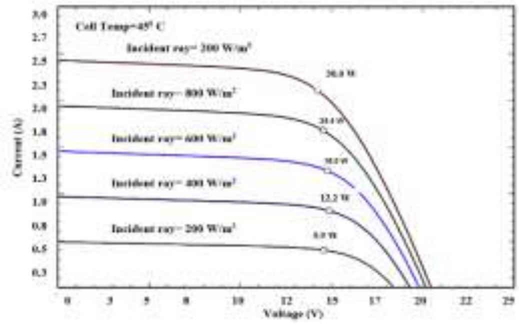


Fig. 1 Efficiency vs temperature graph (Obtained from PVsyst software).

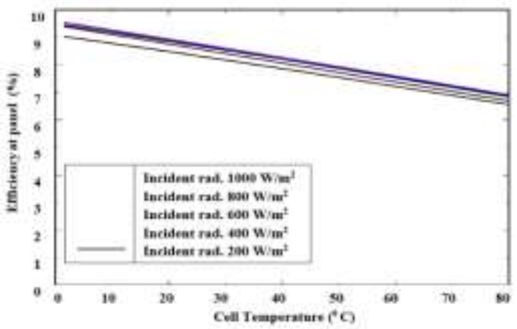


Figure 2. Effect of temperature on the IV characteristics of a 30 W PV module (Obtained from PVsyst software).

2.2. Construction of Test Rig and Its Components

The construction of the test rig is as shown in **Fig. 3.** It includes an aluminium sheet on which the thermoelectric coolers were fixed. A total of 4 thermoelectric coolers were used in the construction of the cooled panel**.**

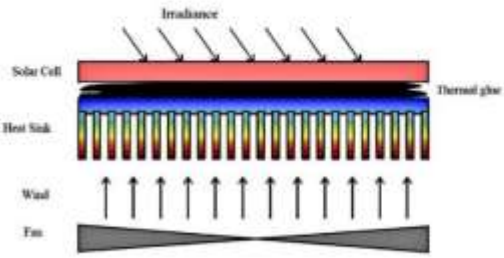
2.2.1. Working Principle for Thermoelectric Coolers

The direct conversion of temperature differences into an electric voltage and conversely converting the electric voltage is into temperature difference is known as thermoelectric effect. Thermoelectric cooler (TEC) which is also known as the "Peltier Cooler" employs the Peltier effect for heat exchange. TEC is made up of P- and N-type semi-conductor couples [43], [44]. A TEC fixed at the rear side of a PV panel with the help of a thermal transfer material with the cold part on the panel and the heat-sink using a good thermal transfer material is mounted on the warm part of the TEC to disperse the warm air into the ambient. In this case, the PV module would be cooled by the TEC as depicted in **Fig. 4**. The working principle of the TEC is presented in **Fig. 5.**

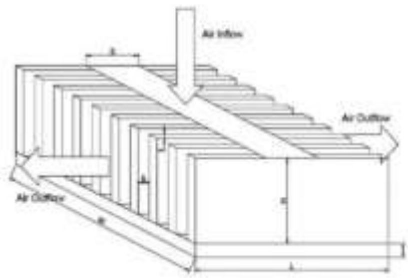
The thermoelectric module (TEM) uses the Peltier effect to provide cooling. The principle behind its working is to generate a heat flux between the P-N junction. The Peltier cooler enables heat transfer from one section of the Peltier module to another part based on the direction of the current. A voltage is applied across the device to get one of the sides hot whiles the other becomes cold. In TECs their performance depends in the ambient temperature, Peltier parameters, the design of the heat exchange as well as the Peltier module's geometry. When a voltage is applied between two dissimilar conductors say A and B, there will be heat at the junction. The rate $\frac{dq}{dt}$ of the heat generated can be expressed as indicated in Eq. (11) [45]. The various parts of the TEC used for the cooling are presented in **Fig. 6**. The parameters of the TEC are presented in **Table 1** and **Table 2**. The experimental test rig in **Fig. 7**.

$$dQ/_{dt} = (\pi_A - \pi_B)I \quad (11)$$

Figure 3. Modified PV module with integrated thermo-electric cooler



(a)



(b)

Figure 4. PV modules (a) Cooling mechanism using TEC (b) flow of air (Modified from [46]).

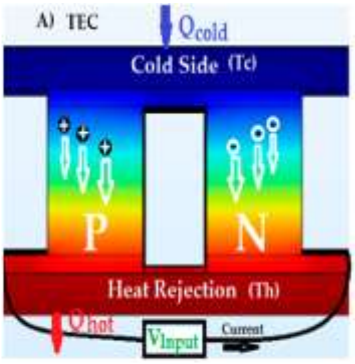


Figure 5. Working principle of TEC [47].

(a)

(b)

(C)

(d)

Figure 6. Parts of the TEC (a) fan for big TEC (b) fan for small TEC (c) heat sink (d) TEC

Table 1. Description of the smaller thermoelectric cooler

Overall Dimension	**40X40X10mm**
Fan Dimension	40X40X10 mm
Net Weight	15.5 g
Bearing Type	Hydro Bearing
Rated Voltage	12V DC
Operating Voltage	10.8～13.2V DC
Started Voltage	7V DC
Consuming Current	0.12 A
Power Input	0.48 W
Fan Speed	4500±10% RPM
Maximum Air Flow	4.82 CFM
Consuming power	1.44 W
Noise	24.3 dB(A)

Table 2. Description of the bigger thermoelectric cooler

Description:	
Model	AV-F9025MS
Name	DC12V BRUSHLESS FAN
Rated Voltage	12V DC
Operation Voltage	DC 6.8-12.8 V
Consuming Current	0.18 A
Consuming Power	2.16 W
Connector	2pin-ph2.5
Rated Speed	3000 R.P.M.
Maximum Air Flow	32.28CFM
Life Expectance	50,000 hours at 25 degrees
Insulation Level	UL Class A
Certificate	UL,CE
Acoustic Noise ***	27.82dB
DC Line Length	200mm
Rotation Direction	Counter-clockwise
Size	80x80x25mm
Weight	40g

2.2.2. Uncertainty Analysis

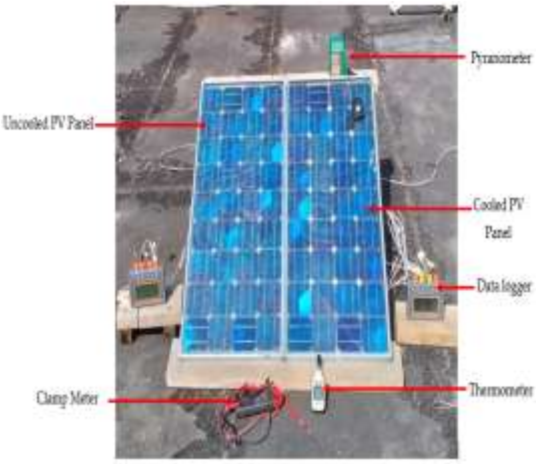
Uncertainty analysis helps to assess the errors that could be associated with the experimental process. The accuracies for the different tools used to record the various values are presented in below**.** The percentage uncertainty can be evaluated using the following relations [21], [48], [49]**.**

$$N = N(Y_1, Y_2, Y_3, \dots Y_n) \qquad (12)$$

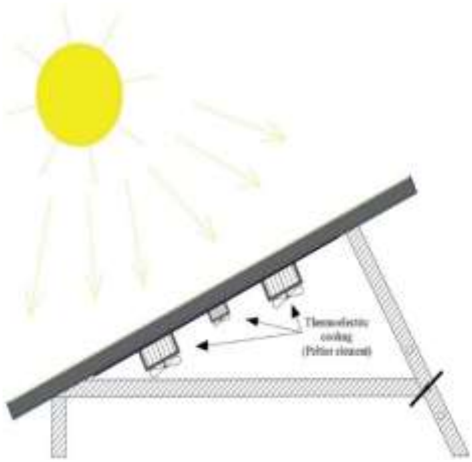
where ΔY_1, ΔY_2 …. ΔY_n are the uncertainties in the independent variables.

The range of the GM 1362-EN-01 thermometer used is −30–70 °C with and accuracy of ±2%, the clamp meter has an accuracy of ±1.5 V, the pyranometer has a range of 0–2000

W/m^2 with an accuracy of ±5 %, the thermocouple also has a range of −200–1370 °C with and accuracy of ±0.1 °C, the anemometer used to measure the wind speed also has a range of 0–25 m/s and an accuracy of 0.2 m/s. The total uncertainty associated with the experiment is calculated to be 3.23%.



(a)



(b)

(c)

Figure 7. The experimental test rig (a) Front view of test rig (b) schematic diagram of test rig (c) rear view of the test rig

3 Results and Discussions

The outcome of the experiment are presented and discussed in this segment; it includes data for the weather characteristics for the experimental period. The section also presents the thermodynamics and economics of the construction of the cooling system.

3.1. Weather Characteristics for the Experimental Period

Fig. 8 gives information on the characteristics of the weather during day of the experiment, as can be seen from the data, the day received quite high solar radiation, an average of 883.07 W/m^2 with an average humidity of 26.82% were recorded in the course of the experiment. The highest solar radiation of 1173 W/m^2 was recorded around 13:30 pm, during this period an ambient temperature of 37.7 ℃ was recorded. The average ambient temperature for the entire period is 32.49 ℃ indicating a relatively hot day. The average wind speed recorded for the period is 5.2 m/s.

3.2. Impact of the Cooling Mechanism on the Panel with Respect to Temperature

A total of seven K- type thermocouples each were utilized to take records of the temperature at the backside of each PV panel. These thermocouples were installed at various positions of both panels. The average temperatures of the seven results for each reading time are presented in **Fig. 9**. The results obtained for the cooled panel indicate that the maximum temperature of 40.50 ℃ happened on 13:30 pm whiles the referenced panel's temperature is 56.09 ℃ at that same period which was also the highest temperature for the referenced panel. It is important to state that the highest temperatures all occurred at a time when the highest ambient temperature was also recorded. The average temperature of the cooled module for the whole period of the experiment is calculated to be 33.37 ℃ whiles that of the referenced module was also estimated to be 45.60 ℃. In effect, the enhanced PV module with integrated thermoelectric cooler was able to decrease the panel's temperature by 12.23 ℃.

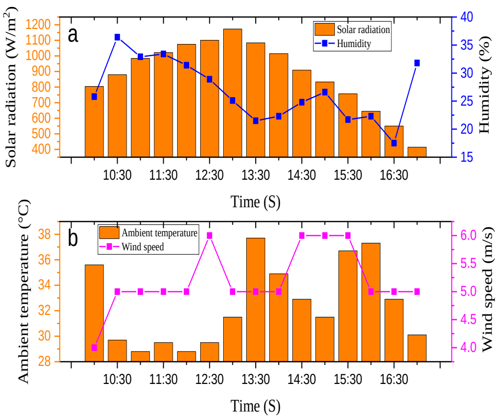


Figure 8. Weather characteristics for the period of experiment (a) solar irradiation (b) ambient temperature

The testo thermal imager was also employed to image the characteristics of the temperature distribution on both panels. The results of same are represented in **Fig. 10**. Results from the infra-red thermal imager, the cooled panel had an average temperature distribution of 33.85 ℃ whereas the referenced module had an average temperature of 45.98 ℃.

3.3. Thermal Management of the PV System Due to Cooling

The power output for both modules were also calculated, the results is as presented in **Fig. 11**. The yield power for the cooled panel is estimated to be 6.31 W whiles that of the referenced module recorded 5.22 W. This implies that the thermoelectric cooling was able to increase the performance of the cooled panel by 1.09 W representing an improvement of 20.88% in the power output using Eq. (14) [50].

$$improvement = \frac{P_{cooled\ PV} - P_{ref\ PV}}{P_{ref\ PV}} \times 100\% \tag{14}$$

The highest difference in power occurred during the period with high temperatures, this suggest that the referenced module as shown in earlier results was affected by its high temperature. The thermoelectric cooler had a positive effect on the output of the cooled module during the hot temperature period. It also introduced some level of stability in the power production which is very important for a plant as solar PV.

The electrical efficiencies of both modules were evaluated using Eq. (3). According to the calculations, the highest efficiency of the referenced module is 14.6% as against 14.8% for the cooled module. The least efficiency of 13.1% for the referenced module was recorded at 13:00 pm, similarly, the cooled panel also recorded its least efficiency of 14.07% at same time. The average electrical efficiency are 13.8% and 14.5% for the referenced and cooled modules, respectively. This translate into a difference of 0.7%, which means that the cooling process was able to enhance the efficiency of the module by some 5.07%. The electrical efficiencies of both PV modules are illustrated in Fig. 12 as well as the improvement in the efficiencies.

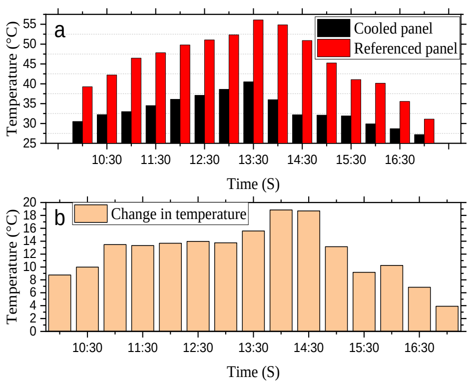
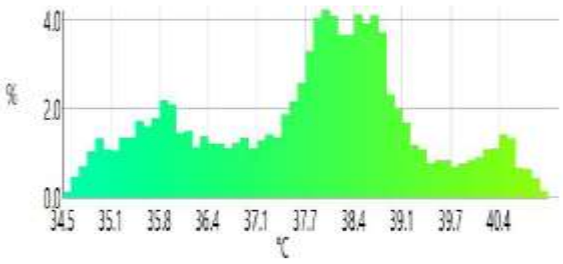
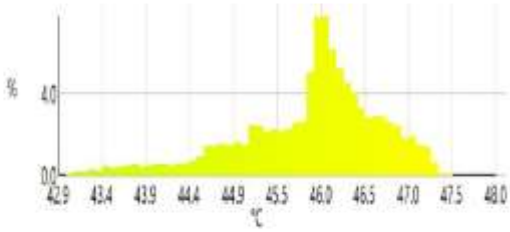


Figure 9. Time dependences (a) assessment of temperature for the two PV panels (b) variation in temperature.



(a)



(b)

Figure 10. Distribution of temperature on the surface of the (a) cooled (b) referenced modules

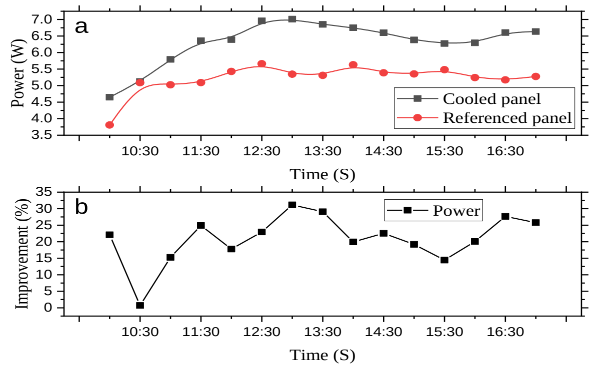


Figure 11. Time dependences (a) Output power for the two modules (b) improvement in power between both modules.

3.4. Economic Analysis

The economics of the PV modules are presented in this section. A number of assumptions were done in this section to obtain a full year electricity generation for both modules. The levelized cost of energy (LCE) which is the most applied method to evaluate the economic viability of power generating projects is used in this analysis. The mathematical relation for the calculation of the LCE are as presented below Eq. (15-20) [21], [51] [52].

$$LCOE = \frac{LC_{inv} + LC_{O\&M} + LC_{fuel}}{E_{annual}} \tag{15}$$

$$LC_{inv} = CRF \times C_{inv} \tag{16}$$

$$CRF = \frac{i_{eff} \cdot (1 + i_{eff})^n}{\left((1 + i_{eff})^n\right) - 1} \tag{17}$$

$$LC_{O\&M} = C_{O\&M} \times CELF \tag{18}$$

$$CELF = \left(K_{O\&M} \times \frac{1 - K_{O\&M}^n}{1 - K_{O\&M}}\right) CRF \tag{19}$$

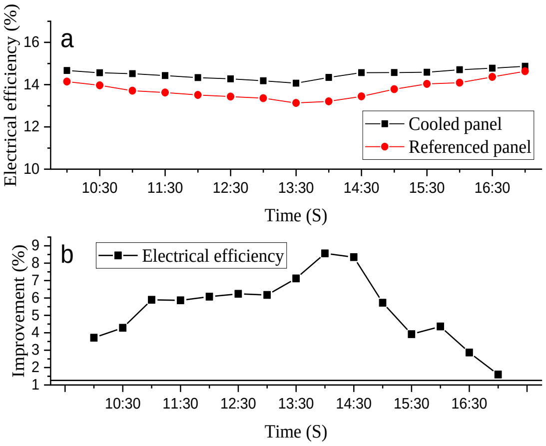


Figure 12. Time dependences (a) Comparison of efficiencies (b) improvement between both panels.

A total of 4 thermoelectric coolers were used in the experiment, details of which are presented above. The cost of the coolers is $5.50 each for the bigger fan and $3.50 each for the smaller fan, this sums up to $18.00 for the four fans used. The 30 W PV panel utilized to conduct the experiment is assumed to be $50 as used in [21]. The cost of the thermal glue used to hold the aluminium plate and the fan at the PV panel's backside to enhance conductivity cost $3.00. The small aluminium plate on which the fans were installed also cost $0.50. Consequently, the whole cost of all materials used for the experiment is $71.5. This study used a yearly operation and maintenance cost $C_{O\&M}$ of $3.50 for both the referenced and cooled panels. The nominal escalation rate and effective discount rate used for the computations are 1% and 5%, respectively [38]. The $\boldsymbol{C_{inv}}$ for the cooled module is $71.5 whiles that of the referenced module is $50.

In effect, a capital recovery factor CRF of 6.50% was obtained, for a 30-year lifetime of the power plant. The $K_{O\&M}$ is calculated to be 0.96 with a $CELF$ of 1.10. The LCE for fuel in this study is 0 $/kWh since the SPP does not require fuel. LC_{inv} of $4.648 is recorded for the cooled module whiles the uncooled module recorded $3.25. In effect, the cooled module registered an LCE of 0.410 $/kWh for the 365 days period whiles the referenced module recorded 0.414 $/kWh for the same period. An amount of 1.247$/kWh was recorded by the cooled panel for the 120-day period whiles the referenced module recorded 1.265 $/kWh. The cooled module still remained relatively cheaper in terms of cost of energy despite the higher investment cost. This is due to the fact that the cooled module generated more power than the referenced module due to the enhancement in the performance of the cooled module.

3.5. *Comparison of Current Results with Other Literature*

Comparing results obtained from the current study to other works as presented in Table 3, it is clear that the results in this study is superior to most of the results obtained by other researchers in terms of the degree of reduction in temperature.

Table 3. Results from previous studies for comparison

Reference	Cooling Mechanism	Temperature reduction (°C)
[53]	Forced convection induced Fans	6.24
[54]	DC brushless fan	6.1
[55]	Fan Cooling	7
[56]	DC brushless Air-Cooling Mechanism	2.56
[57]	Forced air over the heat sink	18.3
[58]	Cooling system on maximum allowable temperature	15
[59]	Air cooling technique DC fan	15.7
[60]	Aluminium heat sink	12.2
[61]	Yellow petroleum jelly	4.3
[62]	PCM-RT35	11
[63]	Fin cooling	5.90
[64]	Microencapsulated phase change material	1.8
[65]	Thermosyhon Heat pipe	10.84
[66]	Heat sink Air cooled	12.5
[67]	Heat sink fins	7.4
[68]	Evaporative Cooling Principle	8
[69]	CPU heat sinks	2.98
Current study	Thermoelectric cooling	12.23

4. Conclusions

This research tested the viability of using thermoelectric coolers as means of managing the temperature of PV modules under high temperature conditions. This is crucial in the solar energy space since the operating temperature of PV cells play key role in the PV cell's performance. The outcome of the experiment through the use of TEC under summer weather conditions of Ekaterinburg in Russia are as follows:

The cooled panel's temperature dropped by 12.23 °C indicating positive impact of the proposed cooling mechanism. This led an enhancement in the efficiency of the cooled module, the average electrical efficiency are 13.8% and 14.5% for the referenced and cooled modules, respectively, this translate into an electrical efficiency enhancement of 5.07%, which is significant. Due to the cooling mechanism installed behind the module, the cooled module had an average power of 6.31 W, whiles the referenced PV panel recorded 5.22 W. This implies that the TEC was able to increase the performance. of the cooled panel by 1.09 W representing an improvement of 20.88%.

The economics of the module suggests that the cooled module registered an LCE of 0.410 $/kWh for the 365 days period whiles the referenced module recorded 0.414 $/kWh for the same period. Despite the relatively high investment cost of the cooled module due to the extra cost associated with the cooling system, it still recorded a relatively lower LCE. This is due to the high power it generated during the experimental period.

It can therefore be concluded that the cooling mechanism is effective considering the parameters assessed and can be used for the cooling of PV modules in hot climatic areas where water is scarce and hence cannot be used for cooling of such power plants. A finite element method can be employed in the future to numerically study the proposed method. This will enhance the design and accuracy of the results.

Abbreviations

CRF	Capital recovery factor
$CELF$	Constant-escalation levelization factor
$O\&M$	Operations and maintenance
DC	Direct current
GHG,	Greenhouse gases
HVAC	Heating, Ventilating and Air Conditioning
inv	Investment
kWh	Kilowatt-hour
LCE	Levelized cost of electricity
$O\&M$	operations and maintenance
PV	Photovoltaic
PCM	Phase change material
PHP	Pulsating heat pipes
RE	Renewable Energy
STC	Standard test conditions
TEC	Thermoelectric cooler
TEM	Thermoelectric module

Nomenclature

°C	Degrees celsius
V_{oc}	Open circuit voltage
P_{mp}	PV module's maximum power
V_m	Maximum Voltage
I_m	Maximum Current
FF	Filling factor
I_{sc}	Short circuit current
η	Efficiency
E_{in} , E_{out}	Energy input, Energy output
T_{pv}	Temperature of the PV
β	Temperature coefficient of power
f_{pv}	Derating factor
Y_{pv}	Rated PV array capacity
α_p	Coefficient of power
T_{cell}	Surface temperature of panel
T_a	Ambient temperature
A	Panel's area
T_s	Sun surface temperature
h_c	Convective heat transfer
v	Wind speed
i_{eff}	Effective discount rate.
r_n	Nominal escalation rate

Funding: The research funding from the Ministry of Science and Higher Education of the Russian Federation (Ural Federal University Program of Development within the Priority-2030 Program) is gratefully acknowledged: Grant number FEUZ-2022-0031.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data used are provided in the text.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] T. S. Adebayo, A. A. Awosusi, S. D. Oladipupo, E. B. Agyekum, A. Jayakumar, and N. M. Kumar, "Dominance of Fossil Fuels in Japan's National Energy Mix and Implications for Environmental Sustainability," *International Journal of Environmental Research and Public Health*, vol. 18, no. 14, Art. no. 14, Jan. 2021, doi: 10.3390/ijerph18147347.

[2] A. G. Andal, S. PraveenKumar, E. G. Andal, M. A. Qasim, and V. I. Velkin, "Perspectives on the Barriers to Nuclear Power Generation in the Philippines: Prospects for Directions in Energy Research in the Global South," *Inventions*, vol. 7, no. 3, Art. no. 3, Sep. 2022, doi: 10.3390/inventions7030053.

[3] E. Shagdar, Y. Shuai, B. G. Lougou, A. Mustafa, D. Choidorj, and H. Tan, "New integration mechanism of solar energy into 300 MW coal-fired power plant: performance and techno-economic analysis," *Energy*, p. 122005, 2021.

[4] T. Sakagami, Y. Shimizu, and H. Kitano, "Exchangeable batteries for micro EVs and renewable energy," in *2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA)*, Nov. 2017, pp. 701–705. doi: 10.1109/ICRERA.2017.8191151.

[5] F. F. Ahmad, C. Ghenai, A. K. Hamid, O. Rejeb, and M. Bettayeb, "Performance enhancement and infra-red (IR) thermography of solar photovoltaic panel using back cooling from the waste air of building centralized air conditioning system," *Case Studies in Thermal Engineering*, vol. 24, p. 100840, Apr. 2021, doi: 10.1016/j.csite.2021.100840.

[6] E. B. Agyekum, S. PraveenKumar, A. Eliseev, and V. I. Velkin, "Design and Construction of a Novel Simple and Low-Cost Test Bench Point-Absorber Wave Energy Converter Emulator System," *Inventions*, vol. 6, no. 1, Art. no. 1, Mar. 2021, doi: 10.3390/inventions6010020.

[7] S. J. Yaqoob, A. L. Saleh, S. Motahhir, E. B. Agyekum, A. Nayyar, and B. Qureshi, "Comparative study with practical validation of photovoltaic monocrystalline module for single and double diode models," *Sci Rep*, vol. 11, no. 1, p. 19153, Dec. 2021, doi: 10.1038/s41598-021-98593-6.

[8] S. J. Yaqoob, S. Motahhir, and E. B. Agyekum, "A new model for a photovoltaic panel using Proteus software tool under arbitrary environmental conditions," *Journal of Cleaner Production*, vol. 333, p. 130074, Jan. 2022, doi: 10.1016/j.jclepro.2021.130074.

[9] S. A. Taya and M. G. Daher, "Properties of Defect Modes of One-Dimensional Quaternary Defective Photonic Crystal Nanostructure," *International Journal of Smart Grid - ijSmartGrid*, vol. 6, no. 2, Art. no. 2, Jun. 2022.

[10] R. Rabie, M. Emam, A. Elwardany, S. Ookawara, and M. Ahmed, "Performance evaluation of concentrator photovoltaic systems integrated with combined passive cooling techniques," *Solar Energy*, vol. 228, pp. 447–463, Nov. 2021, doi: 10.1016/j.solener.2021.09.055.

[11] E. B. Agyekum, S. PraveenKumar, N. T. Alwan, V. I. Velkin, S. E. Shcheklein, and S. J. Yaqoob, "Experimental Investigation of the Effect of a Combination of Active and Passive Cooling Mechanism on the Thermal Characteristics and Efficiency of Solar PV Module," *Inventions*, vol. 6, no. 4, Art. no. 4, Dec. 2021, doi: 10.3390/inventions6040063.

[12] Y. Iwasaki, Y. Kazuto, K. Ikeda, and T. Goto, "A Basic Study on Electricity Demand for Energy Management," in *2021 10th International Conference on Renewable Energy Research and Application (ICRERA)*, Sep. 2021, pp. 301–304. doi: 10.1109/ICRERA52334.2021.9598665.

[13] J. Kim, S. Bae, Y. Yu, and Y. Nam, "Experimental and Numerical Study on the Cooling Performance of Fins and Metal Mesh Attached on a Photovoltaic Module," *Energies*, vol. 13, no. 1, Art. no. 1, Jan. 2020, doi: 10.3390/en13010085.

[14] B. Ramkiran, C. K. Sundarabalan, and K. Sudhakar, "Sustainable passive cooling strategy for PV module: A comparative analysis," *Case Studies in Thermal Engineering*, vol. 27, p. 101317, 2021.

[15] A. Belkaid, I. Colak, K. Kayisli, M. Sara, and R. Bayindir, "Modeling and Simulation of Polycrystalline Silicon Photovoltaic Cells," in *2019 7th International Conference on Smart Grid (icSmartGrid)*, Dec. 2019, pp. 155–158. doi: 10.1109/icSmartGrid48354.2019.8990733.

[16] S. Nižetić, D. Čoko, A. Yadav, and F. Grubišić-Čabo, "Water spray cooling technique applied on a photovoltaic panel: The performance response," *Energy Conversion and Management*, vol. 108, pp. 287–296, Jan. 2016, doi: 10.1016/j.enconman.2015.10.079.

[17] H. Bahaidarah, A. Subhan, P. Gandhidasan, and S. Rehman, "Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions," *Energy*, vol. 59, pp. 445–453, Sep. 2013, doi: 10.1016/j.energy.2013.07.050.

[18] H. Alizadeh, R. Ghasempour, M. B. Shafii, M. H. Ahmadi, W.-M. Yan, and M. A. Nazari, "Numerical simulation of PV cooling by using single turn pulsating heat pipe," *International Journal of Heat and Mass Transfer*, vol. 127, pp. 203–208, Dec. 2018, doi: 10.1016/j.ijheatmasstransfer.2018.06.108.

[19] E. B. Agyekum, S. PraveenKumar, N. T. Alwan, V. I. Velkin, and S. E. Shcheklein, "Effect of dual surface cooling of solar photovoltaic panel on the efficiency of the module: experimental investigation," *Heliyon*, vol. 7, no. 9, p. e07920, Sep. 2021, doi: 10.1016/j.heliyon.2021.e07920.

[20] Y. Zhang, C. Shen, C. Zhang, J. Pu, Q. Yang, and C. Sun, "A novel porous channel to optimize the cooling performance of PV modules," *Energy and Built Environment*, 2021.

[21] E. B. Agyekum, S. PraveenKumar, N. T. Alwan, V. I. Velkin, and T. S. Adebayo, "Experimental Study on Performance Enhancement of a Photovoltaic Module Using a Combination of Phase Change Material and Aluminium Fins—Exergy, Energy and Economic (3E) Analysis," *Inventions*, vol. 6, no. 4, Art. no. 4, Dec. 2021, doi: 10.3390/inventions6040069.

[22] A. M. A. Soliman, H. Hassan, and S. Ookawara, "An experimental study of the performance of the solar cell with heat sink cooling system," *Energy Procedia*, vol. 162, pp. 127–135, Apr. 2019, doi: 10.1016/j.egypro.2019.04.014.

[23] B. Bokor, H. Akhan, D. Eryener, and L. Kajtár, "Theoretical and experimental analysis on the passive cooling effect of transpired solar collectors," *Energy and Buildings*, vol. 156, pp. 109–120, Dec. 2017, doi: 10.1016/j.enbuild.2017.09.063.

[24] M. Lebbi *et al.*, "Energy performance improvement of a new hybrid PV/T Bi-fluid system using active cooling and self-cleaning: Experimental study," *Applied Thermal Engineering*, vol. 182, p. 116033, Jan. 2021, doi: 10.1016/j.applthermaleng.2020.116033.

[25] W. Salameh, C. Castelain, J. Faraj, R. Murr, H. El Hage, and M. Khaled, "Improving the efficiency of photovoltaic panels using air exhausted from HVAC systems: Thermal modelling and parametric analysis," *Case Studies in Thermal Engineering*, vol. 25, p. 100940, Jun. 2021, doi: 10.1016/j.csite.2021.100940.

[26] M. Dida, S. Boughali, D. Bechki, and H. Bouguettaia, "Experimental investigation of a passive cooling system for photovoltaic modules efficiency improvement in hot and arid regions," *Energy Conversion and Management*, vol. 243, p. 114328, Sep. 2021, doi: 10.1016/j.enconman.2021.114328.

[27] A. Kane, V. Verma, and B. Singh, "Optimization of thermoelectric cooling technology for an active cooling of photovoltaic panel," *Renewable and Sustainable Energy Reviews*, vol. 75, pp. 1295–1305, Aug. 2017, doi: 10.1016/j.rser.2016.11.114.

[28] M. Ebrahimi, M. Rahimi, and A. Rahimi, "An experimental study on using natural vaporization for cooling of a photovoltaic solar cell," *International Communications in Heat and Mass Transfer*, vol. 65, pp. 22–30, Jul. 2015, doi: 10.1016/j.icheatmasstransfer.2015.04.002.

[29] A. Ejaz, F. Jamil, and H. M. Ali, "A novel thermal regulation of photovoltaic panels through phase change materials with metallic foam-based system and a concise comparison: An experimental study," *Sustainable Energy Technologies and Assessments*, vol.

49, p. 101726, Feb. 2022, doi: 10.1016/j.seta.2021.101726.

[30] M. Lucas, F. J. Aguilar, J. Ruiz, C. G. Cutillas, A. S. Kaiser, and P. G. Vicente, "Photovoltaic Evaporative Chimney as a new alternative to enhance solar cooling," *Renewable Energy*, vol. 111, pp. 26–37, Oct. 2017, doi: 10.1016/j.renene.2017.03.087.

[31] A. Maleki, P. T. T. Ngo, and M. I. Shahrestani, "Energy and exergy analysis of a PV module cooled by an active cooling approach," *J Therm Anal Calorim*, vol. 141, no. 6, pp. 2475–2485, Sep. 2020, doi: 10.1007/s10973-020-09916-0.

[32] A. M. Elbreki, A. F. Muftah, K. Sopian, H. Jarimi, A. Fazlizan, and A. Ibrahim, "Experimental and economic analysis of passive cooling PV module using fins and planar reflector," *Case Studies in Thermal Engineering*, vol. 23, p. 100801, Feb. 2021, doi: 10.1016/j.csite.2020.100801.

[33] P. Bevilacqua, R. Bruno, and N. Arcuri, "Comparing the performances of different cooling strategies to increase photovoltaic electric performance in different meteorological conditions," *Energy*, vol. 195, p. 116950, Mar. 2020, doi: 10.1016/j.energy.2020.116950.

[34] A. E. Kabeel, M. Abdelgaied, and R. Sathyamurthy, "A comprehensive investigation of the optimization cooling technique for improving the performance of PV module with reflectors under Egyptian conditions," *Solar Energy*, vol. 186, pp. 257–263, Jul. 2019, doi: 10.1016/j.solener.2019.05.019.

[35] K. P. Amber, W. Akram, M. A. Bashir, M. S. Khan, and A. Kousar, "Experimental performance analysis of two different passive cooling techniques for solar photovoltaic installations," *J Therm Anal Calorim*, vol. 143, no. 3, pp. 2355–2366, Feb. 2021, doi: 10.1007/s10973-020-09883-6.

[36] R. Nasrin, N. A. Rahim, H. Fayaz, and M. Hasanuzzaman, "Water/MWCNT nanofluid based cooling system of PVT: Experimental and numerical research," *Renewable Energy*, vol. 121, pp. 286–300, 2018.

[37] Q. Luo, P. Li, L. Cai, X. Chen, H. Yan, H. Zhu, P. Zhai, P. Li, and Q. Zhang "Experimental investigation on the heat dissipation performance of flared-fin heat sinks for concentration photovoltaic modules," *Applied Thermal Engineering*, vol. 157, p. 113666, 2019.

[38] A. A. B. Baloch, H. M. S. Bahaidarah, P. Gandhidasan, and F. A. Al-Sulaiman, "Experimental and numerical performance analysis of a converging channel heat exchanger for PV cooling," *Energy Conversion and Management*, vol. 103, pp. 14–27, Oct. 2015, doi: 10.1016/j.enconman.2015.06.018.

[39] S. Dubey, J. N. Sarvaiya, and B. Seshadri, "Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World – A Review," *Energy Procedia*, vol. 33, pp. 311–321, Jan. 2013, doi: 10.1016/j.egypro.2013.05.072.

[40] L. Idoko, O. Anaya-Lara, and A. McDonald, "Enhancing PV modules efficiency and power output using multi-concept cooling technique," *Energy Reports*, vol. 4, pp. 357–369, Nov. 2018, doi: 10.1016/j.egyr.2018.05.004.

[41] R. Ramkumar, M. Kesavan, C. M. Raguraman, and A. Ragupathy, "Enhancing the performance of photovoltaic module using clay pot evaporative cooling water," in *2016 International Conference on Energy Efficient Technologies for Sustainability (ICEETS)*, Apr. 2016, pp. 217–222. doi: 10.1109/ICEETS.2016.7582929.

[42] E. B. Agyekum, "Techno-economic comparative analysis of solar photovoltaic power systems with and without storage systems in three different climatic regions, Ghana," *Sustainable Energy Technologies and Assessments*, vol. 43, p. 100906, Feb. 2021, doi: 10.1016/j.seta.2020.100906.

[43] H. C. Kuttarmare, R. D. Vaidya, S. M. Chaudhari, K.G.Sontakke, Y. G. Joshi, A. R. Gupta, , A. R Raghatate, and D.K. Padal "Fabrication of Peltier Cooling System: Alternative for Refrigeration." IJARIIE, 2016.

[44] M. A. Qasim, N. T. Alwan, S. PraveenKumar, V. I. Velkin, and E. B. Agyekum, "A New Maximum Power Point Tracking Technique for Thermoelectric Generator Modules," *Inventions*, vol. 6, no. 4, Art. no. 4, Dec. 2021, doi: 10.3390/inventions6040088.

[45] M. Benghanem, A. A. Al-Mashraqi, and K. O. Daffallah, "Performance of solar cells using thermoelectric module in hot sites," *Renewable Energy*, vol. 89, pp. 51–59, Apr. 2016, doi: 10.1016/j.renene.2015.12.011.

[46] E. K. A. Fatoni, A. Taqwa, and R. Kusumanto, "Solar Panel Performance Improvement using Heatsink Fan as the Cooling Effect," *J. Phys.: Conf. Ser.*, vol. 1167, p. 012031, Feb. 2019, doi: 10.1088/1742-6596/1167/1/012031.

[47] K. Teffah, Y. Zhang, and X. Mou, "Modeling and Experimentation of New Thermoelectric Cooler–Thermoelectric Generator Module," *Energies*, vol. 11, no. 3, Art. no. 3, Mar. 2018, doi: 10.3390/en11030576.

[48] N. T. Alwan, S. E. Shcheklein, O. M. Ali, M. H. Majeed, and E. B. Agyekum, "Experimental and Theoretical Investigations of a Modified Single-Slope Solar Still with an External Solar Water Heater," *Sustainability*, vol. 13, no. 22, Art. no. 22, Jan. 2021, doi: 10.3390/su132212414.

[49] N. T. Alwan, S. E. Shcheklein, and O. M. Ali, "Experimental investigation of modified solar still integrated with solar collector," *Case Studies in Thermal Engineering*, vol. 19, p. 100614, Jun. 2020, doi: 10.1016/j.csite.2020.100614.

[50] S. PraveenKumar, E. B. Agyekum, V. I. Velkin, S. J. Yaqoob, and T. S. Adebayo, "Thermal management of solar photovoltaic module to enhance output performance: an experimental passive cooling approach using discontinuous aluminium heat sink," *International Journal of Renewable Energy Research (IJRER)*, vol. 11, no. 4, Art. no. 4, Dec. 2021.

[51] N. T. Alwan, M. H. Majeed, S. E. Shcheklein, O. M. Ali, and S. PraveenKumar, "Experimental Study of a Tilt Single Slope Solar Still Integrated with Aluminium

Condensate Plate," *Inventions*, vol. 6, no. 4, Art. no. 4, Dec. 2021, doi: 10.3390/inventions6040077.

[52] S. Praveenkumar, A. Gulakhmadov, A. Kumar, M. Safaraliev, and X. Chen, "Comparative Analysis for a Solar Tracking Mechanism of Solar PV in Five Different Climatic Locations in South Indian States: A Techno-Economic Feasibility," *Sustainability*, vol. 14, no. 19, Art. no. 19, Jan. 2022, doi: 10.3390/su141911880.

[53] A. R. Amelia Y.M. Irwan, M. Irwanto, W.Z. Leow, N. Gomesh, I. Safwati, and M.A.M. Anuar, "Cooling on photovoltaic panel using forced air convection induced by DC fan," *International Journal of Electrical and Computer Engineering*, vol. 6, no. 2, pp. 526–534, 2016, doi: 10.11591/ijece.v6i1.9118.

[54] Y. M. Irwan, W. Z. Leow, M. Irwanto, M. Fareq, S. I. S. Hassan, I. Safwati and A. R. Amelia, "Comparison of solar panel cooling system by using dc brushless fan and dc water," *Journal of Physics: Conference Series*, vol. 622, no. 1, 2015, doi: 10.1088/1742-6596/622/1/012001.

[55] H. Erol, M. Uçman, and Z. Kesilmiş, "The Effect of Fan Cooling on Photovoltaic Efficiency of PV Panels in Osmaniye Environment," vol. 6, no. 3, pp. 29–33, 2017.

[56] Y. M. Irwan, W. Z. Zeow, M. Irwanto, M. Fareq, A. R. Amelia, N.Gomesh, and I. Safwati "Analysis air cooling mechanism for photovoltaic panel by solar simulator," International Journal of Electrical and Computer Engineering, vol. 5, no. 4, pp. 636–643, 2015, doi: 10.11591/ijece.v5i4.pp636-643.

[57] A. M. A. Soliman, H. Hassan, and S. Ookawara, "An experimental study of the performance of the solar cell with heat sink cooling system," *Energy Procedia*, vol. 162, pp. 127–135, 2019, doi: 10.1016/j.egypro.2019.04.014.

[58] J. Hallal, M. Hammoud, and T. Moussa, "Experimental optimization of the Si photovoltaic panels cooling system on maximum allowable temperature criteria," *Renewable Energy Focus*, vol. 35, no. December, pp. 178–181, 2020, doi: 10.1016/j.ref.2020.10.007.

[59] T. N. Sultan, M. S. Farhan, and H. T. H. Salim Alrikabi, "Using Cooling System for Increasing the Efficiency of Solar Cell," *Journal of Physics: Conference Series*, vol. 1973, no. 1, 2021, doi: 10.1088/1742-6596/1973/1/012129.

[60] E. Mahone, Mark and B. Denckla, Martha, "untitled _ Enhanced Reader.pdf," *Clinical Infectious Diseases*. 2017.

[61] Y. S. Indartono, A. Suwono, and F. Y. Pratama, "Improving photovoltaics performance by using yellow petroleum jelly as phase change material," *International Journal of Low-Carbon Technologies*, vol. 11, no. 3, pp. 333–337, 2016, doi: 10.1093/ijlct/ctu033.

[62] H. Mahamudul, M. Silakhori, I. Henk Metselaar, S. Ahmad, and S. Mekhilef, "Development of a temperature regulated photovoltaic module using phase change material for Malaysian weather condition," *Optoelectronics and Advanced Materials, Rapid Communications*, vol. 8, no. 11–12, pp. 1243–1245, 2014.

[63] M. Chandrasekar and T. Senthilkumar, "Passive thermal regulation of flat PV modules by coupling the mechanisms of evaporative and fin cooling," *Heat and Mass Transfer/Waerme- und Stoffuebertragung*, vol. 52, no. 7. pp. 1381–1391, 2016. doi: 10.1007/s00231-015-1661-9.

[64] C. J. Ho, W. L. Chou, and C. M. Lai, "Thermal and electrical performance of a water-surface floating PV integrated with a water-saturated MEPCM layer," *Energy Conversion and Management*, vol. 89. pp. 862–872, 2015. doi: 10.1016/j.enconman.2014.10.039.

[65] L. Habeeb, D. Ghanim, L. J. Habeeb, D. Ghanim Mutasher, F. A. Muslim, and A. Ali, "Cooling Photovoltaic Thermal Solar Panel by Using Heat Pipe at Baghdad Climate," *International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS*, vol. 17, no. February, p. 6, 2017.

[66] Z. Arifin, D. D. D. P. Tjahjana, S. Hadi, R. A. Rachmanto, G. Setyohandoko, and B. Sutanto, "Numerical and experimental investigation of air cooling for photovoltaic panels using aluminium heat sinks," *International Journal of Photoenergy*, vol. 2020, 2020, doi: 10.1155/2020/1574274.

[67] M. Firoozzadeh, A. H. Shiravi, and M. Shafiee, "An Experimental Study on Cooling the Photovoltaic Modules by Fins to Improve Power Generation: Economic Assessment," *Iranian Journal of Energy and Environment*, vol. 10, no. 2, pp. 80–84, 2019, doi: 10.5829/ijee.2019.10.02.02.

[68] Z. A. Haidar, J. Orfi, and Z. Kaneesamkandi, "Photovoltaic panels temperature regulation using evaporative cooling principle: Detailed theoretical and real operating conditions experimental approaches," *Energies*, vol. 14, no. 1, 2021, doi: 10.3390/en14010145.

[69] S. Praveenkumar, A. Gulakhmadov, E. B. Agyekum,N. T. Alwan, V. I. Velkin, P. Sharipov, M. Safaraliev, and X. Chen., "Experimental Study on Performance Enhancement of a Photovoltaic Module Incorporated with CPU Heat Pipe—A 5E Analysis," *Sensors*, vol. 22, no. 17, Art. no. 17, Jan. 2022, doi: 10.3390/s22176367.